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APPLICATION FOR UNITED STATES LETTERS PATENT

FOR

FIBER-OPTIC GAUGE HAVING ONE OR MORE SIDE-MOUNTED SENSORS

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FIBER-OPTIC GAUGE HAVING ONE OR MORE SIDE-MOUNTED SENSORS

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to the field of instrumentation and, more specifically, to sensing devices, such as fiber-optic gauges.

Description of the Related Art

Miniature fiber-optic gauges may be used in a variety of applications. For example, a gauge having a pressure sensor may be inserted into a patient's artery to monitor blood pressure during a medical procedure such as an angioplasty.

A representative prior art fiber-optic gauge available from FISO Technologies, Inc., of Quebec, Canada is based on a Fabry-Perot interferometer (FPI). The gauge has a sensor formed by two mirrors that define the interferometer cavity. The cavity is coupled to an optical fiber and acts as a wavelength modulator whose reflection (transmission) characteristics depend on the cavity length. For example, a beam of light having a flat (i.e., wavelength-independent or "white") spectrum is reflected back from the cavity as a beam of light whose spectrum is a periodic function of wavelength. By appropriately analyzing the reflected light, e.g., as described in U.S. Patent Nos. 5,202,939 and 5,392,117, the teachings of both of which are incorporated herein by reference, the cavity length can be measured. The obtained length value may then be related to an external physical parameter, such as strain, stress, pressure, or temperature, affecting the cavity length.

One problem with prior-art fiber-optic gauges is that each sensor is mounted at a terminus of a dedicated optical fiber. As a result, when measurements need to be performed simultaneously at more than one location, a fiber-optic gauge having multiple optical fibers has to be used, where each fiber is dedicated to a corresponding sensor. Such a gauge may be relatively complex and difficult to handle. In addition, in certain applications, the use of gauges having multiple fibers may not be possible at all. For example, the use of such gauges during certain medical procedures would increase the patient's trauma and/or risk of complications and therefore should preferably be avoided.

SUMMARY OF THE INVENTION

Problems in the prior art are addressed, in accordance with the principles of the invention, by a fiber-optic gauge having at least one sensor mounted onto a side of an optical fiber. In one embodiment, the sensor is optically coupled to the fiber using a thin-film filter inserted into the fiber and preferably oriented at about 45 degrees with respect to the fiber axis. The sensor may be one of a plurality of sensors similarly mounted on and optically coupled to a single optical fiber. Each sensor is designed to change its reflectivity in response to a change in an external physical parameter, e.g., pressure, and is preferably adapted for interrogation with monochromatic light. The interrogating light has a plurality of wavelength components, each corresponding to a different sensor. Light reflected from the sensors is de-multiplexed and analyzed to measure the reflectivity of each sensor and to derive the corresponding value of the physical parameter, thereby providing a parameter measurement at each sensor location. Advantageously, gauges of the invention may be used in medical applications such as arterial catheterization to provide, e.g., real-time blood-pressure sampling around a damaged area of an artery, while decreasing the patient's trauma compared to that inflicted by prior-art devices where multiple optical fibers are used for a similar measurement.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a cross-sectional view of a fiber-optic gauge according to one embodiment of the present invention;

Fig. 2 shows a cross-sectional view of a terminus-mounted pressure sensor that can be used in the gauge of Fig. 1 according to one embodiment of the present invention;

Fig. 3 shows a perspective three-dimensional view of a side-mounted pressure sensor that can be used in the gauge of Fig. 1 according to one embodiment of the present invention;

Fig. 4 shows a block diagram of a gauge interrogation device according to one embodiment of the present invention, where the device is configured to interrogate the fiber-optic gauge of Fig. 1; and

Fig. 5 shows a partial cut-away perspective view of a portion of a medical device according to one embodiment of the present invention.

DETAILED DESCRIPTION

Reference herein to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment can be included in at least one embodiment of the invention. The appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments mutually exclusive of other embodiments.

Fig. 1 shows a cross-sectional view of a fiber-optic gauge **100** according to one embodiment of the present invention. Gauge **100** has two sensors **104** and **106** that are coupled to an optical fiber **102** and mounted on a side and at the terminus, respectively, of the fiber. Fiber **102** has a thin-film filter **108** inserted into the fiber and preferably oriented at 45 degrees with respect to the axis of the fiber. Filter **108** is designed to reflect light corresponding to sensor **104** and to transmit light corresponding to sensor **106**. Gauge **100** also has an optional jacket **110** placed around fiber **102** and sensors **104** and **106**.

In one embodiment, to insert filter **108** into fiber **102**, the fiber is sliced at 45 degrees with respect to its longitudinal axis to expose the fiber core. The filter is deposited onto one of the exposed surfaces of the sliced fiber to cover at least a portion of the fiber core. Various deposition methods well known in the art, such as, for example, spray coating or chemical vapor deposition, may be used for the filter deposition. The fiber portions are then reconnected and secured together to have the filter sandwiched between said portions.

During operation, sensors **104** and **106** are interrogated by a beam of light having at least two wavelength components labeled λ_1 and λ_2 in Fig. 1, where component λ_1 corresponds to sensor **104** and component λ_2 corresponds to sensor **106**. Component λ_1 launched along fiber **102** toward the sensors takes the following optical path: it (i) reaches filter **108**, (ii) is reflected by the filter toward sensor **104**, (iii) reaches the sensor, (iv) is reflected back by the sensor (thereby interrogating the sensor), (v) again reaches the filter, and (vi) is reflected by the filter in the direction opposite to the initial propagation direction. Similarly, component λ_2 reaches filter **108**, passes through the filter toward sensor **106**, reaches the sensor, is reflected back by the sensor in the direction opposite to the initial propagation direction (thereby interrogating the sensor), and again reaches and passes through the filter.

As indicated by the above description, one difference between fiber-optic gauge **100** (Fig. 1) and a typical prior-art gauge is that gauge **100** has a side-mounted sensor (i.e., sensor **104**) that is mounted on fiber **102** and is optically coupled to the fiber core using filter **108**, while, in prior-art gauges, sensors are terminus-mounted. Another difference is that different sensors in gauge **100** are designed for interrogation with light of different wavelengths. As a result of these differences, a single optical fiber can be used to support a plurality of sensors. This is advantageously different from prior-art gauges, where a plurality of optical fibers is used to support a plurality of sensors.

Fig. 2 shows a cross-sectional view of a pressure sensor **206** that can be used as sensor **106** in gauge **100** according to one embodiment of the present invention. More specifically, sensor **206** is similar to a sensor disclosed in commonly owned U.S. Patent No. 5,831,262, the teachings of which are incorporated herein by reference. Briefly, sensor **206** includes a sealed chamber **210** defined by (i) a layer **214** having a movable portion **218** and (ii) a fixed layer **216**, both layers supported on a substrate layer **212**. Fixed layer **216** is attached to an optically transparent (e.g., glass) layer **226** to which the terminus of fiber **102** is glued using a transparent cement layer **224**. Layers **224** and **226** are preferably index-matched to core **222** of fiber **102**. Movable portion **218** of layer **214** is exposed to external pressure through an opening **208** in substrate layer **212** and can move in response to pressure changes. For example, when the pressure in opening **208** exceeds the pressure in chamber **210**, portion **218** moves toward fixed layer **216**. Similarly, when the pressure in opening **208** is lower than the pressure in chamber **210**, portion **218** moves away from fixed layer **216**. Portion **218** is in equilibrium when the total force exerted on the portion by the pressure in chamber **210**, the pressure in opening **208**, and elastic deformation of layer **214** is equal to zero.

Central portions **220** and **230** of layers **214** and **216**, respectively, are optically coupled to fiber core **222** and form a Fabry-Perot interferometer (FPI) of sensor **206**, which FPI has variable cavity length due to the mobility of portion **220**. In contrast to prior-art sensors that are designed for interrogation with white light, sensor **206** is designed to be preferably interrogated with monochromatic light, for example, at wavelength λ_2. The cavity length and thereby the pressure in opening **208** can be derived based on the reflectivity of the FPI. More details on the optical response of the FPI in sensor **206**, pressure determination

based on said response, and methods of manufacture can be found in the above-cited '262 patent.

Fig. 3 shows a perspective three-dimensional view of a pressure sensor **304** that can be used as sensor **104** in gauge **100** according to one embodiment of the present invention. Sensor **304** is similar to sensor **206** (Fig. 2) with corresponding structural elements of the two sensors labeled in Figs. 2 and 3 using numerals having the same last two digits. However, one difference between sensors **304** and **206** is in the shape of their respective glass layers **326** and **226**. More specifically, glass layer **326** of sensor **304** has an opening **332** into which fiber **102** may be inserted sideways and glued using a transparent cement layer similar to cement layer **224** of Fig. 2. Another difference between sensors **304** and **206** is that sensor **304** is designed to be interrogated using a different wavelength than sensor **206**, for example, wavelength λ_1. In one implementation, the spacing between λ_1 and λ_2 is on the order of 100 nm.

Fig. 4 shows a block diagram of a gauge interrogation device **400** according to one embodiment of the present invention, where device **400** is configured to interrogate gauge **100** of Fig. 1. Device **400** includes two light sources (e.g., laser diodes) **402a-b** configured to generate monochromatic light at wavelengths λ_1 and λ_2, respectively. Light generated by sources **402a-b** is (i) multiplexed using an optical multiplexer (MUX) **404** and (ii) coupled into fiber **102** of gauge **100** via an optical circulator **406**. After interrogating sensors **104** and **106** of gauge **100** as described above and exiting fiber **102**, the reflected light is directed by circulator **406** to an optical de-multiplexer (DMUX) **408**, where it is decomposed into two beams having light at λ_1 and λ_2, respectively. Each beam is then applied to a corresponding receiver **410a** or **410b**, e.g., to measure the beam intensity. The response of each receiver is processed, e.g., as described in the above-cited '262 patent, to obtain a pressure value for the corresponding sensor of gauge **100**. In a different embodiment, a gauge interrogation device similar to device **400** may be constructed to have more than two light sources and receivers, where each light source/receiver pair corresponds to a different sensor operating at a different wavelength in a fiber-optic gauge analogous to gauge **100**.

Fig. 5 shows a partial cut-away perspective view of a portion of a medical device **500** according to one embodiment of the present invention. Device **500** includes an intra-aortic balloon (IAB) catheter **550** that is similar to an IAB co-lumen catheter available from Datascope Corp. of Montvale, NJ. Catheter **550** has an external tube **552** enclosing an

internal tube **554**, which is attached to the inner wall of the external tube. External tube **552** has two openings **556a-b**, each sized and shaped to accommodate a corresponding pressure sensor **504a/504b**, while internal tube **554** accommodates an optical fiber **502** having thin-film filters **508a-b**. Fiber **502**, each of filters **508**, and each of sensors **504** are similar to fiber **102**, filter **108**, and sensor **104**, respectively, of fiber-optic gauge **100** (Fig. 1). Each sensor **504** is inserted into the corresponding opening **556** and attached to fiber **502** such that the corresponding filter **508** is aligned with the sensor. After the sensor insertion, openings **556a-b** are sealed such that sensors **504a-b** remain exposed on the exterior of external tube **552**. When device **500** is inserted into a blood vessel (e.g., an aorta), sensors **504a-b** can be used to monitor blood pressure at their respective locations. An additional sensor (not shown) similar to sensor **106** of Fig. 1 may be attached at the terminus of fiber **502** to monitor fluid pressure inside catheter **550**. Advantageously, during a medical procedure, device **500** may be positioned in a blood vessel such that a damaged area of the vessel, e.g., a blood clot, is located between sensors **504a** and **504b** thereby sampling blood pressure around the damaged area.

While this invention has been described with reference to illustrative embodiments, this description is not intended to be construed in a limiting sense. Although the invention was described in reference to fiber-optic gauges having pressure sensors, other (strain, stress, temperature, etc.) optically interrogated sensors may similarly be used. Furthermore, a gauge of the invention may include sensors of two or more different types, for example, a pressure sensor and a temperature sensor. A fiber-optic gauge of the invention may include one or more of side-mounted sensors (e.g., sensors **104**) and none or one of terminus-mounted sensors (e.g., sensor **106**). Different sensors may be designed for light of different wavelengths including ultra-violet, visible, and infrared light. Each individual sensor may be designed for interrogation with more than one wavelength, e.g., two wavelengths or a wavelength band, to provide data redundancy. Optical properties of each thin-film filter can be tailored to reflect light corresponding to the sensor associated with the filter and to transmit light corresponding to all other sensors. In systems without a terminus-mounted sensor, a metal (e.g., gold) film can be used in place of the filter having the far-most downstream location (e.g., filter **508b** in device **500**). Different types of fiber, e.g., bend-insensitive, multimode, etc., may be used in the gauges of the invention. Various modifications of the described embodiments, as well as other embodiments of the invention,

which are apparent to persons skilled in the art to which the invention pertains are deemed to lie within the principle and scope of the invention as expressed in the following claims.

Although the steps in the following method claims, if any, are recited in a particular sequence with corresponding labeling, unless the claim recitations otherwise imply a particular sequence for implementing some or all of those steps, those steps are not necessarily intended to be limited to being implemented in that particular sequence.